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Ice drift derived from the Polar Ice Prediction System (PIPS) is used to study the sea ice circulation of the Beaufort and Chukchi seas in the late summer. Model simulations for the years 1983, 1986 and 1987 show that the anticyclonic Beaufort Gyre reverses to cyclonic circulation in the late summer. This result is due to a change in the mean atmospheric surface pressure. Drifting buoys from 1983 confirm this reversal of the Beaufort Gyre.



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# A NUMERICAL MODEL SIMULATION OF A SUMMER REVERSAL OF THE BEAUFORT GYRE

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Abstract. Ice drift derived from the Polar Ice Prediction System (PIPS) is used to study the sea ice circulation of the Beaufort and Chukchi seas in the late summer. Model simulations for the years 1983, 1986 and 1987 show that the anticyclonic Beaufort Gyre reverses to cyclonic circulation in the late summer. This result is due to a change in the mean atmospheric surface pressure. Drifting buoys from 1983 confirm this reversal of the Beaufort Gyre.

## Introduction

The Polar Ice Prediction System (PIPS) is a sea ice forecasting system designed for the Arctic, which has the capability of predicting ice drift, ice thickness and ice concentration. The PIPS model, developed jointly by the Naval Ocean Research and Development Activity (NORDA) and the Fleet Numerical Oceanography Center (FNOC), is run daily by FNOC.

The Hibler ice model [Hibler, 1979] serves as the basis for PIPS. The ice model is driven by atmospheric forcing from the Naval Operational Global Atmospheric Prediction System (NOGAPS) [Preller, 1985] and monthly mean ocean currents and ocean heat fluxes derived from the Hibler and Bryan ice-ocean model [Hibler and Bryan, 1987]. The system forecasts over the entire Arctic basin, the Barents sea and the northern half of the Greenland and Norwegian seas.

PIPS is run every day making a 120 hour forecast of ice drift, ice thickness and ice concentration. Each day the model is initialized from the previous day's 24 hour forecast. Once per week, the model derived ice concentration field is updated by Arctic ice concentration data made available by the Naval Polar Oceanography Center (NPOC). No additional observational data is incorporated into the model at any other time. Along with the 120 hour forecast made by FNOC, a 24 hour forecast has been made and archived daily by NORDA, since June 1986, as a means of monitoring the model.

This study will focus on ice drift fields which have been derived by PIPS during 1987 and with ice drift derived from the Hibler model tested with 1983 and 1986 NOGAPS data. The only difference between the PIPS results and the test cases for 1983 and 1986, is that the PIPS ice concentration field was updated weekly and resulted in a better estimate of the ice edge location. This difference does not impact the results presented in this study.

The ice model has been shown by Hibler [1979] to be capable of reproducing the average annual ice drift in the Arctic. This average pattern of ice drift is defined by a large anticyclonic circulation in the vicinity of the Beaufort sea called the Beaufort Gyre and a transpolar drift which begins near the Siberian coast and extends through the Fram Strait [Gordienko, 1958]. Walsh et al. [1985] found that the Hibler ice model, when driven by 30 years of atmospheric forcing, showed interannual variability in the annual mean pattern. The Beaufort Gyre and the transpolar drift existed in all cases, but varied in intensity from year to year. They also found that the Beaufort Gyre varied seasonally in size and shape. Model results averaged over 30 years showed that the gyre was large during spring and fall, covering the western third of the Arctic basin. In winter, the gyre covered the western quarter of the Arctic and in summer, it was reduced to a small gyre in the Beaufort sea.

This study will show that when model results are further broken down into monthly means during the summer, a distinct change takes place in the standard pattern of ice drift. The Beaufort Gyre is seen to reverse from anti-cyclonic to cyclonic circulation in the late summer. This reversal has also been observed in Arctic buoy data [McLaren et. al, 1987].

## The Model

The Polar Ice Prediction System is based on the dynamic/thermodynamic Hibler ice model [Hibler, 1979]. The PIPS ice model has five major components: a momentum balance, a viscous-plastic ice rheology, an ice thickness distribution, an ice strength relationship and an air-ice-ocean heat balance [Preller, 1985]. This study is mainly concerned with the momentum balance used to determine ice drift:

$$m \frac{D\vec{u}}{Dt} = m f k \times \vec{u} + \vec{\tau}_a + \vec{\tau}_w - mg \text{ grad } H + \vec{F} \quad (1)$$

where $m$ is the ice mass per unit area, $\vec{u}$ is the ice velocity, $f$ is the Coriolis parameter, $\vec{\tau}_a$ and $\vec{\tau}_w$ are the air and water stresses, $g$ is the acceleration of gravity, $H$ is the sea surface dynamic height and $F$ is the force due to the variation in internal ice stress. Ice moves in a two dimensional field with forcing applied through simple boundary layer formulations. The air and water stresses are defined

$$\vec{\tau}_a = \rho_a C_a |\vec{U}_g| (\vec{U}_g \cos \phi + k \times \vec{U}_g \sin\phi) \quad (2)$$

$$\vec{\tau}_w = \rho_w C_w |\vec{U}_w - \vec{u}| [(\vec{U}_w - \vec{u}) \cos \theta + k \times (\vec{U}_w - \vec{u}) \sin \theta] \quad (3)$$

where $\vec{u}$ is the ice drift, $\vec{U}_g$ is the geostrophic wind, $\vec{U}_w$ is the geostrophic ocean current, $C_a$



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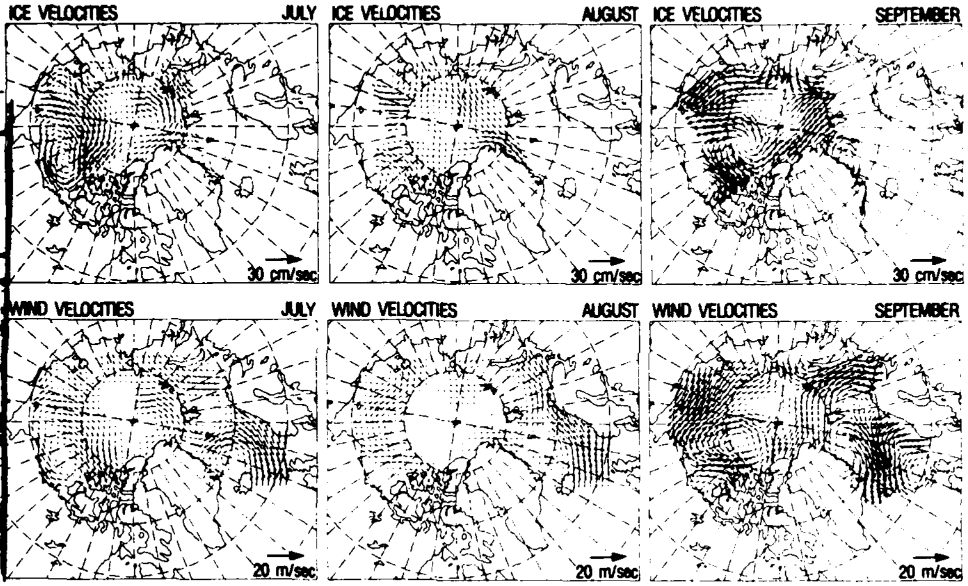




Fig. 1. 1983 monthly mean model ice drift from a) July, b) August and c) September. Vector scale is 30 cm/sec. 1983 monthly mean NOGAPS geostrophic winds for d) July, e) August and f) September. Vector scale is 20 m/sec.



and $C_w$ are the air and water drag coefficients, $\rho_a$ and $\rho_w$ are the air and water densities and $\phi$ and $\theta$ are the air and water turning angles. Surface pressure fields from the atmospheric model are used to calculate geostrophic wind. Surface stresses are then estimated from the geostrophic winds using a turning angle of 23° and a drag coefficient of $.8 \times 10^{-3}$. This drag coefficient was chosen to give the best agreement between PIPS ice drift magnitudes and the observed ice drift magnitudes from Arctic buoys. For the oceanic boundary layer, the ice velocity relative to the currents beneath the boundary layer is used to calculate a quadratic water drag. The turning angle and drag coefficient used in the calculations are 25° and $5.5 \times 10^{-3}$ respectively [McPhee, 1980].

The PIPS domain covers the central Arctic, Barents sea and the northern Greenland sea. The model grid spacing is 127 km and is defined on the northern hemisphere polar-stereographic grid used by FNOC. The model uses a 6 hour time step in order to resolve daily variability in the atmospheric heat fluxes.

## Results

The Hibler ice model, when forced by NOGAPS atmospheric forcing for 1983, 1986 and 1987, along with the ocean currents and heat fluxes from the Hibler and Bryan ice-ocean model, shows annual and seasonal mean ice drift similar to that found by Hibler [1979] and Walsh et al. [1985]. An interesting trend is seen when the summer season is broken down into monthly means. When forced by 1983 NOGAPS data, the ice model shows a small anticyclonic circulation confined to the Beaufort sea during the months of July and August (Figures 1a and 1b). However, the September monthly mean ice drift (Figure 1c) shows a distinct cyclonic circulation covering the Beaufort and Chukchi seas and extending into the central Arctic. The gyre weakens from July through August and then completely reverses from its normal anticyclonic to cyclonic drift in September. During October, the monthly mean circulation reverts back into the small anticyclonic gyre seen during July and August.

The circulation of the gyre closely corresponds to the monthly mean wind forcing, Figures 1 d-f. Geostrophic winds from NOGAPS indicate mean clockwise motion in July. In August, the clockwise circulation has become very weak in the Beaufort sea. By September, the winds are rotating counterclockwise over the Beaufort and Chukchi seas.

During 1983, the Arctic Ocean Buoy Program, run by the University of Washington's Polar Science Center, had from 6-13 buoys in the Arctic during the July - September time period [Colony and Munoz, 1985]. These buoys provide information on position, temperature and atmospheric surface pressure. Colony and Munoz have also created charts showing daily surface pressure fields over the Arctic. During the period of July through September, 1983, these surface pressure charts show a change in the mean pressure in the Beaufort sea. During July, high pressure dominated the Beaufort sea region approximately 67% of the month, while in August it drops to about 55%. During September the average surface pressure pattern changes and low pressure dominates the Beaufort sea approximately 70% of the month. This data was compared to maps of surface pressure fields from the National Meteorological Center (NMC). The two data sets agree very well during these summer months. Monthly mean surface pressures from Colony and Munoz [1985] (Figures 2 a-c) also compare very closely to the NOGAPS monthly means (Figures 2 d-f). One would expect good agreement between these two data sets since buoy data are incorporated into the NOGAPS initialization scheme. Figure 2f has included the displacement of four different buoys in the region of the Beaufort gyre during the month of September. All of the buoys indicate counter-clockwise

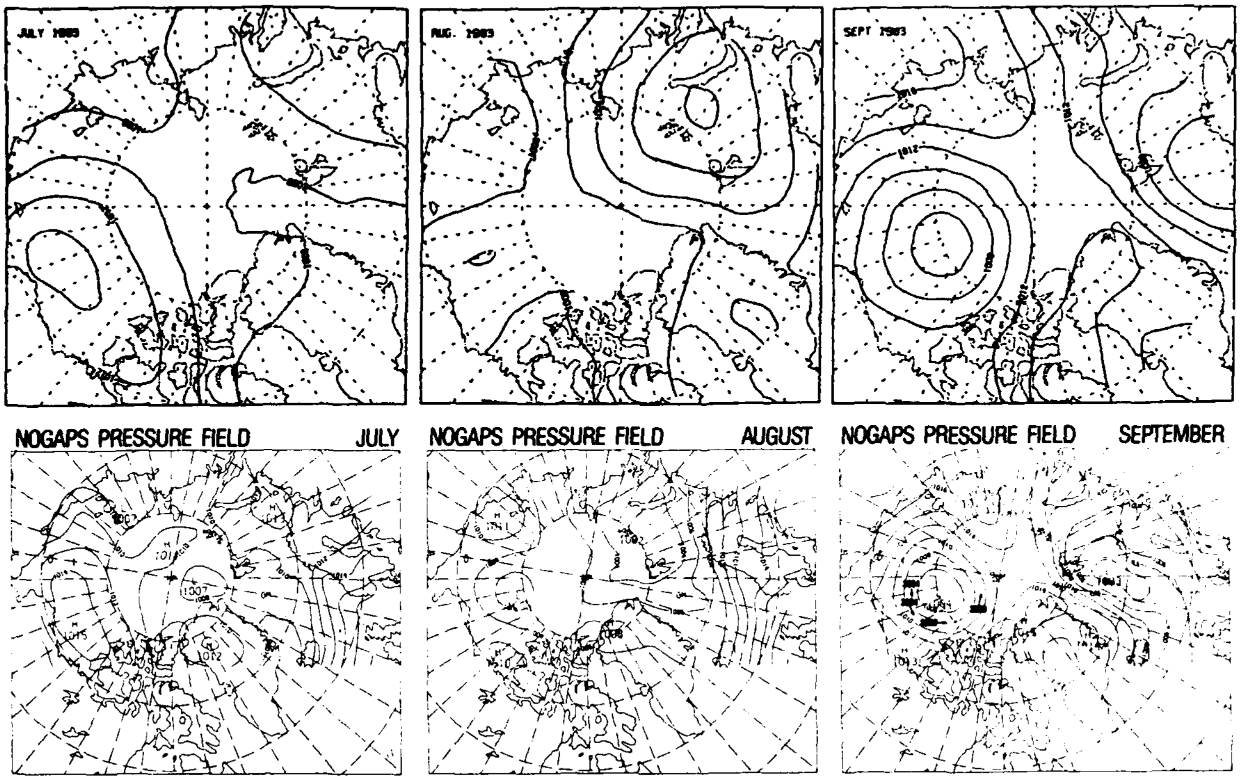


Fig. 2. 1983 monthly mean surface pressure fields derived from buoy data (Colony and Munoz, 1985) for a) July, b) August and c) September. 1983 NOGAPS monthly mean surface pressure fields for d) July e) August and f) September. The displacement of 4 buoys during the month of September is included. Contour interval is 2 mb.

motion during this month in agreement with the model results (Figure 1c).

For the annual average, PIPS ice drift appears to be an almost equal combination of both the annual average ocean currents and the annual average wind field. However, on daily, weekly and monthly time scales, the wind field dominates the ice motion. Thus, during the summer months when high pressure dominates the Beaufort sea region, an anticyclonic gyre results. However, when a low pressure field dominates, as in September, 1983, the monthly mean circulation of the gyre is cyclonic.

This summertime reversal of the gyre is also found when the ice model is driven by 1986 NOGAPS atmospheric forcing. However, in 1986, the reversal appears earlier in the summer (Figures 3 a-c). During July, anticyclonic drift appears as the monthly mean in the Beaufort sea. A cyclonic gyre dominates the Beaufort and Chukchi seas in August. In September, the cyclonic gyre still exists but has shifted to the northeast. As in the 1983 case, the drift responds directly to the circulation induced by the atmospheric surface pressure. The 1986 NOGAPS surface pressure fields show good comparison, on a day by day basis, with the NMC surface pressure fields. Low pressure systems dominate the Beaufort and Chukchi seas during August and most of September. The dominance of low pressure observed in this region is not due to a stationary system but rather a series of low pressure systems that move into and out of the area. The longest period of time that a low pressure system was observed to have remained in the Beaufort and Chukchi seas was seven days. High pressure systems appeared interspersed between these lows but remained in the region for a shorter period of time.

Results from the PIPS model during 1987 (Figures 3 d-f) show a large anticyclonic Beaufort Gyre in July which weakens dramatically during August. In September, a reversed Beaufort Gyre exists however it is shifted to the west of the cyclonic Beaufort Gyre found in the summers of 1983 and 1986. As in the two previous cases, the monthly mean drift correlates closely to the monthly mean wind forcing.

## Conclusions

This study shows that numerical ice models do simulate a reversal of the Beaufort Gyre in the late summer. The PIPS model when driven by monthly mean ocean currents and heat fluxes and NOGAPS atmospheric forcing shows a similar trend in the monthly mean ice drift during the three test years; 1983, 1986 and 1987. The trend is defined as a deterioration of the normal anti-cyclonic Beaufort Gyre of spring and early summer into a complete reversal of the gyre's circulation in August or September. This change in the gyre's circulation is due to a change in the basic pattern of atmospheric surface pressure in this region of the Arctic. The area is normally dominated by high pressure systems. However in the late summer low pressure systems appear more frequently in the Beaufort and Chukchi seas.

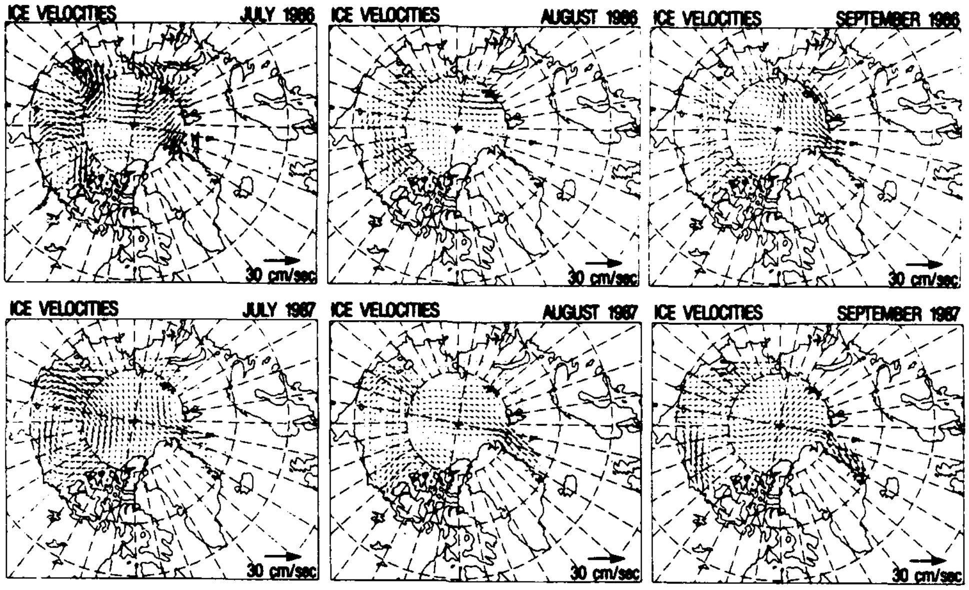


**Fig. 3.** 1986 monthly mean model ice drift from a) July, b) August and c) September. 1987 monthly mean PIPS ice drift from a) July, b) August and c) September. Vector scale is 30 cm/sec.

Similar results have recently been reported by McLaren et al. [1987]. Upon examining seven years worth of buoy data (1979-1985) from the Arctic Buoy Program, McLaren et al. conclude that there is "a reoccuring tendency for reversal of the mean clockwise gyre in late summer," due to a change from anticyclonic to a quasi-stationary cyclonic circulation in the atmosphere in the vicinity of the Beaufort gyre. They also state that previous testing of the Hibler model by Hibler and Tucker [1979] and Walsh et al. [1985] "failed to indicate any cyclonic pattern" in a summer simulation of ice motion. This study shows that the Hibler ice model does indeed predict a reversal of the gyre in the late summer. This reversal varies inter-annually being stronger during 1983 and 1986 then during 1987. This trend may not have appeared in the work previously published by Hibler and Tucker and by Walsh et al. because they discussed annual and seasonal means. The reversal, which appears for only one to two months in the late summer, is not seen in the annual mean and may not appear in the summer seasonal average. Also, the appearance of this reversal during the three test years does not prove that it occurs every year.

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